Title

Application of HYDRUS (2D/3D) for Predicting the Influence of Subsurface Drainage on Soil Water Dynamics in a Rainfed-Canola Cropping System

Permalink

Authors

Karandish, F
Darzi-Naftchali, A
Šimůnek, J

Publication Date

2018-08-01

DOI

10.1002/ird.2194

Peer reviewed

IRRIGATION AND DRAINAGE
Irrig. and Drain. **67** (Suppl. 2): 29–39 (2018)
Published online 6 December 2017 in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ird.2194

APPLICATION OF HYDRUS (2D/3D) FOR PREDICTING THE INFLUENCE OF SUBSURFACE DRAINAGE ON SOIL WATER DYNAMICS IN A RAINFED-CANOLA CROPPING SYSTEM†

FATEMEH KARANDISH[1]*, ABDULLAH DARZI-NAFTCHALI[2] AND JIŘÍ ŠIMŮNEK[3]

[1]*Water Engineering Department, University of Zabol, Zabol, Iran*
[2]*Water Engineering Department, Sari Agricultural Sciences and Natural Resources University, Sari, Iran*
[3]*Department of Environmental Sciences, University of California, Riverside, Riverside, California, USA*

ABSTRACT

The HYDRUS (2D/3D) model was applied to investigate the probable effects of different subsurface drainage systems on the soil water dynamics under a rainfed-canola cropping system in paddy fields. Field experiments were conducted during two rainfed-canola growing seasons on the subsurface-drained paddy fields of the Sari Agricultural Sciences and Natural Resources University, Mazandaran Province, northern Iran. A drainage pilot consisting of subsurface drainage systems with different drain depths and spacings was designed. Canola was cultivated as the second crop after the rice harvest. Measurements of the groundwater table depth and drain discharge were taken during the growing seasons. The performance of the HYDRUS-2D model during the calibration and validation phases was evaluated using the model efficiency (EF), root mean square error (RMSE), normalized root mean square error (NRMSE) and mean bias error (MBE) measures. Based on the criteria indices (MBE = 0.01–0.17 cm, RMSE = 0.05–1.02 and EF = 0.84–0.96 for drainage fluxes, and MBE = 0.01–0.63, RMSE = 0.34–5.54 and EF = 0.89–0.99 for groundwater table depths), the model was capable of predicting drainage fluxes as well as groundwater table depths. The simulation results demonstrated that HYDRUS (2D/3D) is a powerful tool for proposing optimal scenario to achieve sustainable shallow aquifers in subsurface-drained paddy fields during winter cropping.

KEY WORDS: HYDRUS (2D/3D); drainage flux; dynamic simulation; paddy field; water table

Received 10 August 2017; Revised 30 September 2017; Accepted 1 October 2017

RÉSUMÉ

Le modèle HYDRUS (2D/3D) a été appliqué pour étudier les effets probables de différents systèmes de drainage souterrain sur la dynamique de l'eau du sol dans le système de culture du colza pluvial implanté dans des rizières. Des expériences sur le terrain ont été menées pendant deux saisons de culture de colza pluvial dans les rizières drainées de l'Université des sciences agricoles et des ressources naturelles de Sari, province de Mazandaran, dans le nord de l'Iran. Un pilote de drainage était composé de drains enterrés à différentes profondeurs et différents écartements. Le colza a été cultivé comme deuxième récolte après la récolte de riz. Des mesures de la profondeur de nappe et de débit ont été effectuées pendant les saisons de croissance. La performance du modèle HYDRUS-2D lors des phases d'étalonnage et de validation a été évaluée à l'aide de l'efficacité du modèle (EF), de l'erreur carrée moyenne (RMSE), de l'erreur carrée moyenne normalisée (NRMSE) et des mesures de l'erreur de biais moyen (MBE). Sur la base des indices de critères (MBE = 0.01–0.17 cm, RMSE = 0.05–1.02 et EF = 0.84–0.96 pour les flux de drainage, et MBE = 0.01–0.63, RMSE = 0.34–5.54 et EF = 0.89–0.99 pour profondeurs de nappe), le modèle était capable de prédire les flux de drainage ainsi que les profondeurs de la nappe phréatique. Les résultats de la simulation ont démontré que la gestion de la nappe souterraine peut être une stratégie efficace pour maintenir les aquifères à faible profondeur dans les rizières drainées pendant la culture hivernale.

MOTS CLÉS: HYDRUS (2D/3D); flux de drainage; simulation dynamique; rizière; ; niveau hydrostatique

*Correspondence to: Fatemeh Karandish, Water Engineering Department, University of Zabol, Zabol, Iran. Tel.: +98 9126753901. E-mail: karandish_h@yahoo.com; f.karandish@uoz.ac.ir
†Application d'HYDRUS (2D/3D) pour la prédiction de l'influence du drainage souterrain sur la dynamique de l''eau dans sol dans un système de culture pluvial de colza.

INTRODUCTION

Subsurface drainage in poorly drained paddy fields of northern Iran provides suitable conditions for growing winter crops, mainly by improving soil conditions by lowering the groundwater table below the root zone, creating a deeper aerobic zone, enabling faster soil drying, and improving the root zone soil conditions (Jafari-Talukolaee *et al*., 2016). Improved crop productivity may readily justify the installation costs of subsurface drainage systems and provide suitable conditions for the adaptation of such technology by local farmers. Although subsurface drainage provides suitable conditions for winter cropping by combating the waterlogging problem, it also alters the soil water dynamics. Therefore, further research is required to analyse such effects under different drainage systems.

Field investigations assessing the long-term consequences of different subsurface drainage systems are usually restricted by high costs. However, some general knowledge is required in the planning and optimizing stages of drainage projects prior to their implementation on a large scale. Simulation models, which are effective tools for capturing soil–water–crop interactions, have been developed during the past decades (Wagenet and Hutson, 1989; Wessolek, 1989; Vanclooster *et al*., 1996; Van Dam *et al*., 1997; Fernández *et al*., 2002; Cameira *et al*., 2003; Panigrahi and Panda, 2003; Neitsch *et al*., 2005; Nishat *et al*., 2007). Of the different models, HYDRUS (2D/3D) (Šimůnek *et al*., 2008, 2016) is one of the most widely used dynamic, physically based models to simulate soil water dynamics (e.g. Cote *et al*., 2003; Skaggs *et al*., 2004; Ajdari *et al*., 2007; Rahil, 2007; Crevoisier, 2008; Lazarovitch *et al*., 2009; Siyal and Skaggs, 2009; Mubarak, 2009; Ramos *et al*., 2012; Tafteh and Sepaskhah, 2012; Karandish and Šimůnek, 2016a, b). One of the advantages of this model is that its input parameters are closely related to soil physical properties, which could be measured either *in situ* or in the laboratory (Karandish and Šimůnek, 2016b). Moreover, since the input parameters of HYDRUS (2D/3D) are directly related to soil, crop and climate properties, the model often provides superior predictions than simpler soil water balance models.

Several earlier studies applied HYDRUS (2D/3D) for predicting soil–water–crop interactions in paddy fields (Janssen and Lennartz, 2009; Garg *et al*., 2009; Tan *et al*., 2014; Li *et al*., 2014, 2015) because of its flexibility in accommodating different types of boundary conditions for water flow and solute transport calculations and its capability to simultaneously consider root uptake of water and nutrients (Li *et al*., 2015). The results of these studies generally emphasized the high capability of this model to simulate water and nutrient fluxes at the field scale. Both HYDRUS-1D and HYDRUS (2D/3D) have been reported to be capable of simulating water and nitrogen dynamics in paddy fields (Tan *et al*., 2014, 2015), even in a multi-layered paddy soil (Tan *et al*., 2014). The applicability of HYDRUS-1D for determining soil water dynamics under preferential flow was also demonstrated by Garg *et al*. (2009), who did research in a multi-layer paddy soil. Using HYDRUS-1D, water and nutrient flow was also accurately simulated by Li *et al*. (2014, 2015) for direct-seeded rice fields. However, a literature review revealed that no research has been yet conducted on the applicability of the HYDRUS (2D/3D) model to analyse the effects of drainage systems on soil water dynamics during winter cropping in poorly drained paddy fields. Therefore, the main objective of this research was to use collected experimental data involving groundwater table drawdown and water balance components to evaluate the capability of the HYDRUS (2D/3D) model to predict daily fluctuations of drainage fluxes and groundwater table depths during a second cropping on subsurface-drained paddy fields.

MATERIALS AND METHODS

Field trial

A field study was conducted during two rainfed canola growing seasons (2011–2012 and 2015–2016) on the 4.5 ha consolidated paddy field at the Sari Agricultural Sciences and Natural Resources University in Mazandaran Province of northern Iran (Figure 1). The area is located in the coastal zone of the eastern part of the Caspian Sea. The climate of the region is alternately influenced by cold Arctic air, humid temperate air from the Atlantic Ocean, dry and cold air associated with Siberian high pressure zones, and Mediterranean warm air. The soil on the site is silty clay and clay to a depth of 300 cm. The saturated hydraulic conductivities of different layers of the soil profile are very low. Table I provides hydraulic parameters and soil physical properties for different soil layers in the study area. The complex hydrological system presented in Table I is common for paddy soils. Puddling is traditionally done to reduce water loss from lowland rice fields. After puddling, the root zone undergoes structural changes leading to the formation of a layered profile with a hydraulically less conductive plough sole below the root zone (Garg *et al*., 2009). This layer is called the ‘hardpan’ layer, which causes water to flow horizontally from between the drains to the backfilled trench in a surface soil layer and then vertically into the drains (Ogino and Ota, 2007).

Eleven PVC corrugated drain pipes (100 m long, with an outside diameter of 100 mm) were installed at the study site in June–July of 2011 at depths of 0.65 and 0.9 m and spacing of 15 and 30 m. Four different subsurface drainage systems were analysed by installing drains at different

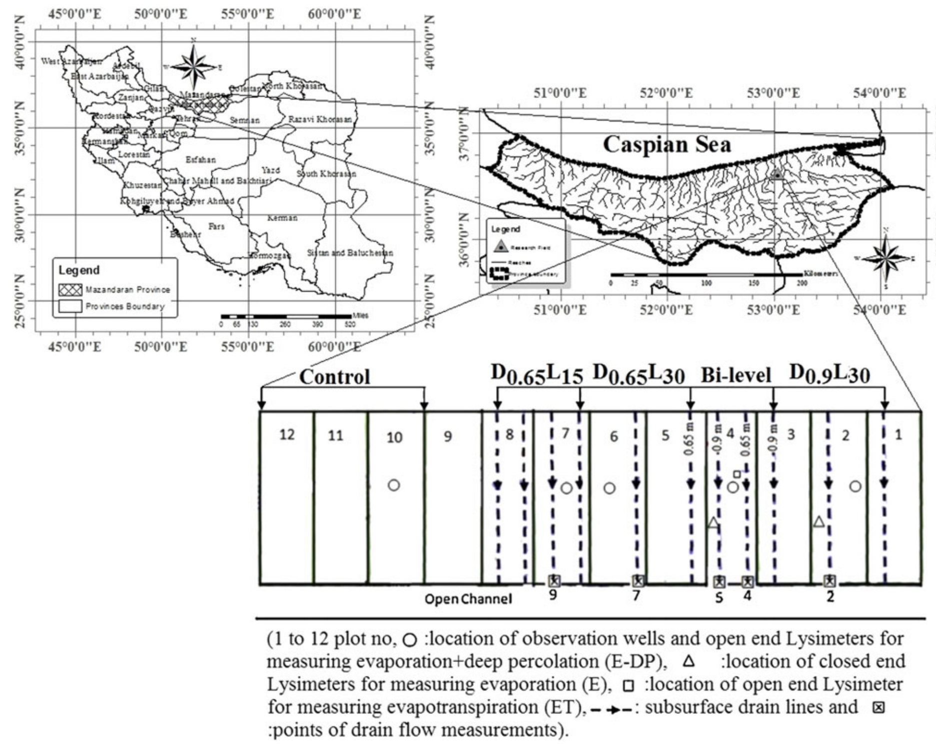

Figure 1. Location of the study area in the Mazandaran Province (top right) of Iran (top left) and the layout of the drainage systems (bottom). [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. Physical properties and hydraulic parameters of different soil layers in the study area

Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	Soil texture	θ_r	θ_s	α (cm^{-1})	n	l	K_s (cm day^{-1})
0–30	48.5	44.4	7	Silty clay	0.001	0.40	0.004	1.19	0.5	25.6
30–60	55.5	42	2.5	Silty clay	0.001	0.40	0.008	1.12	0.5	8.1
60–90	46.5	45.5	8	Silty clay	0.192	0.40	0.008	1.36	0.5	20.7
90–120	42.5	51.5	6	Silty clay	0.098	0.40	0.006	1.42	0.5	16.3
120–150	52	42	6	Silty clay	0.001	0.57	0.004	1.27	0.5	10.9
150–200	58.5	35.5	6	Clay	0.229	0.59	0.004	1.47	0.5	8.3

θ_r and θ_s are the residual and saturated water contents, respectively, reported on a volumetric basis, K_s is the saturated hydraulic conductivity, and α, n, and l are the shape factors in the van Genuchten–Mualem model (van Genuchten, 1980).

depths (D_x, where subscript x indicates a drain depth in metres) and spacing (L_y, where subscript y indicates a drain spacing in metres): $D_{0.9}L_{30}$, $D_{0.65}L_{30}$ and $D_{0.65}L_{15}$. The last drainage system, denoted as Bilevel, has a drain spacing of 15 m and alternate drain depths of 0.65 and 0.9 m. Further details about the experimental design can be found in Darzi-Naftchali *et al*. (2013). Figure 1 shows the location of the research field in the country and the layout of the drainage systems in the research field.

Before crop cultivation, soil samples were taken from each drainage system plot every 30 cm to a depth of 200 cm. Soil physical and chemical properties were determined from these soil samples. Soil water contents at 14 different pressure heads (from 0 to 16 bar) were measured in the laboratory using a pressure plate apparatus. The van Genuchten–Mualem model (van Genuchten, 1980) was then fitted to the observed retention curves using the RETention Curve (RETC) model. Crops were then sown on 28 November 2011 and 3 October 2015. All agricultural operations followed the conventional practices of the local growers in the study area. Daily measurements of groundwater table depths were made manually in the observation wells that were dug midway between drains. Moreover, drainage discharge was measured daily in all drainage systems. Drains were only plugged during the last month of the growing season before harvest. Crops were harvested on 8 May 2012 and 3 May 2016.

SIMULATION APPROACH

HYDRUS (2D/3D) (Šimůnek *et al*., 2008) is a powerful software for simulating transient, two- or three-dimensional movement of water and nutrients in soils for a wide range of boundary conditions, irregular boundaries and soil heterogeneities. Water flow in soils is described using the Richards equation as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - \frac{\partial k}{\partial z} - \mathrm{WU}(h, x, z) \tag{1}$$

where θ is the volumetric soil water content (SWC) [L^3 L^{-3}], K is the unsaturated hydraulic conductivity [LT^{-1}], h is the soil water pressure head [L], x is the lateral coordinate [L], z is the vertical coordinate (positive downwards), t is time [T], and WU(h, r, z) denotes root water uptake [T^{-1}]. WU is computed as follows:

$$\mathrm{WU}(h, x, z) = \gamma(h)\mathrm{RDF}(x, z)WT_{\mathrm{pot}} \tag{2}$$

where $\gamma(h)$ is the soil water stress function (dimensionless) of Feddes *et al*. (1978), RDF is the normalized root water uptake distribution [L^{-2}], T_{pot} is the potential transpiration rate [LT^{-1}], and W is the width of the soil surface [L] associated with the transpiration process. The values recommended by Tafteh and Sepaskhah (2012) were adopted for the coefficients of the Feddes equation. Although root distribution data were measured weekly, the root distribution was assumed to be uniform in time during each simulation period (which is a restriction of HYDRUS).

The van Genuchten–Mualem constitutive relationships (van Genuchten, 1980) were applied for modelling soil hydraulic properties. A rectangle 200 cm deep (since the impermeable layer was at the 200 cm soil depth) and either 30 m wide for the $D_{0.9}L_{30}$ and $D_{0.65}L_{30}$ drainage systems or 15 m wide for the $D_{0.65}L_{15}$ and Bilevel drainage systems was defined as a two-dimensional transport domain in the model. The transport domain was discretized using an unstructured, triangular, finite element mesh (FEM). A non-uniform FEM was generated by HYDRUS (2D/3D) with finite element sizes gradually increasing with distance from the drains. Six soil horizons with different soil hydraulic properties were defined for the 0–30, 30–60, 60–90, 90–120, 120–150 and 150–200 cm soil depths (Table I). An additional soil layer was considered to represent the backfilled drain trench (gravel), with a higher hydraulic conductivity above and around drains.

The measured pressure head distribution was applied to define the initial conditions for flow simulations. The atmospheric boundary condition was applied at the top of the transport domain. The interactions between soil and atmosphere were described using the atmospheric time-variable boundary condition and measured meteorological data. Potential evapotranspiration (ET_0) was calculated using the FAO 56 Penman–Monteith method (Allen *et al*., 1998), while soil evaporation (E_p) and crop transpiration (T_p) were determined according to the dual crop coefficient approach (Allen *et al*., 1998):

$$\mathrm{ET_p} = E_p + T_p = k_e \times \mathrm{ET_0} + k_{cb} \times \mathrm{ET_0} \tag{3}$$

where ET_p is crop evapotranspiration, E_p is soil evaporation (mm), T_p is crop transpiration, and k_e and k_{cb} are soil evaporation and crop basal coefficients, respectively. Standard canola k_{cb} values, suggested by Allen *et al*. (1998), were 0.4, 0.95 and 0.25 for the initial, mid-season and the end of the late-season growth stages, respectively. These values were adjusted for the local climate, taking into consideration the crop height, wind speed and minimum relative humidity averages for the period under consideration. Figure 2 shows

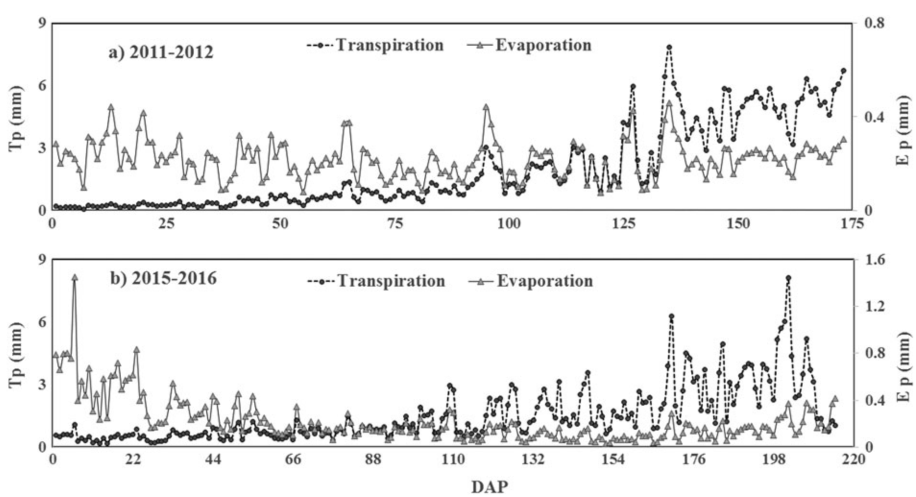

Figure 2. Daily potential soil evaporation (*Ep*) and potential transpiration (*Tp*) estimated using the dual crop coefficient approach during 2011–2012 (a) and 2015–2016 (b) growing seasons. DAP represents the number of days after planting.

daily potential transpiration ($k_{cb} \times ET_0$) and soil evaporation ($k_e \times ET_0$) during the 2011–2012 and 2015–2016 growing seasons. These values were then used as time-variable boundary conditions in the model, along with precipitation received at the site during the experimental periods.

The seepage face boundary condition was used to represent the drains during the drainage periods. All other remaining boundaries were assigned a no-flow boundary condition.

Daily measured drainage fluxes (DF) as well as groundwater table depths (WD) during the 2011–2012 growing season were used to calibrate the HYDRUS (2D/3D) model for all drainage systems. During the calibration process, the saturated hydraulic conductivity (K_s), the residual soil water content (θ_r), and the saturated soil water content (θ_s) were optimized using the inverse analysis of HYDRUS (2D/3D) and measured WD, while the shape parameters α, n and l in the van Genuchten–Mualem model (van Genuchten, 1980) were kept equal to values obtained by the RETC model. Finally, the accuracy of HYDRUS (2D/3D) was assessed using the criteria indices such as mean bias error (MBE), root mean square error (RMSE) and model efficiency (EF) (Parchami-Araghi *et al.*, 2013):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \tag{4}$$

$$MBE = \frac{\sum_{i=1}^{n}(O_i - P_i)}{n} \tag{5}$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O_i}\right)^2} \tag{6}$$

where P_i and O_i are the predicted and observed data, respectively, $\overline{O}$ and $\overline{P}$ are the averages of observed and simulated data, respectively, and n is the number of observations.

RESULTS AND DISCUSSION

Temporal variations of the observed and simulated drainage fluxes (DF) for different drainage systems as well as the related scatter plots are displayed in Figure 3 for the calibration period. The determination coefficients of 0.93–0.96 reveal a good agreement between the observed and simulated daily DF for all drainage systems when the optimized soil hydraulic parameters were used during the calibration period. A higher R^2 (0.96) was obtained for $D_{0.65}L_{15}$ where DF were higher, while $D_{0.9}L_{30}$ with observed DF in the range of 0–2.25 mm day^{-1} had the lowest R^2 (0.93). Figure 3 shows that HYDRUS (2D/3D) performed very well in simulating average DF during the growing season of 2011–2012. The average observed DF for the Bilevel, $D_{0.65}L_{15}$, $D_{0.65}L_{30}$ and $D_{0.9}L_{30}$ drainage systems in the 2011–2012 growing season were 1.6, 2.66, 0.69 and 1.37 mm day^{-1}, respectively, while the corresponding simulated values were, 1.61, 2.69, 0.7 and 1.38 mm day^{-1}, respectively.

Figure 4 shows the temporal fluctuation of simulated and observed daily water depths (WD) for different drainage systems for the 2011–2012 growing season. HYDRUS (2D/3D) was able to capture the temporal trend of WD for all drainage systems. WD fluctuations during this period were mainly due to variations in precipitation, evaporation and crop water demand, as well as percolation. Except for a few days in the $D_{0.9}L_{30}$ and $D_{0.65}L_{15}$ drainage systems, the HYDRUS (2D/3D) model slightly underestimated WD during the calibration periods (Figure 4). In this period, the determination coefficients were 0.96, 0.90, 0.86 and 0.94 for the $D_{0.9}L_{30}$, Bilevel, $D_{0.65}L_{30}$ and $D_{0.65}L_{15}$ drainage systems, respectively. The average observed WD for the Bilevel, $D_{0.65}L_{15}$, $D_{0.65}L_{30}$, and $D_{0.9}L_{30}$ drainage systems during the measuring period of the 2011–2012 growing season were −15.0, −2.1, −24.1, and −32.0 cm, respectively, while the corresponding simulated values were −14.5, −2.5, −24.0, and −33 cm, respectively.

While the results given in Figures 3 and 4 indicate the strong predictive capabilities of the HYDRUS (2D/3D) model, some minor differences between measured and simulated water contents were still observed. These differences can be partly explained by the representation of soil heterogeneity in the model. While soil texture and hydraulic parameters usually change gradually in the soil profile (Tan *et al.*, 2015), six distinct soil layers with different soil hydraulic parameters were defined in the model. Increasing the number of soil layers or gradually varying soil hydraulic parameters may improve the simulation results. However, the simulated DF and WD agree well overall with measured data, as indicated by the statistical measures for the model performance (Table II). The performance of the HYDRUS (2D/3D) model in simulating DF and WD in terms of RMSE, MBE and EF is summarized in Table II. For the calibration period, the RMSE values characterizing differences between observed and simulated DF were 0.09 mm day^{-1} for the $D_{0.9}L_{30}$, 0.11 mm day^{-1} for the Bilevel, 0.05 mm day^{-1} for $D_{0.65}L_{30}$ and 0.18 mm day^{-1} for the $D_{0.65}L_{15}$. Despite a slight overestimation (MBE = 0.01–0.02 mm day^{-1}), the EF values, ranging from 0.92 to 0.96, indicated that the simulated DF agreed well with the observed values for all drainage systems during the calibration period. In addition, having RMSE = 0.37–2.23 cm, MBE = −0.01–0.25 cm and EF = 0.96–0.99, the HYDRUS (2D/3D)-simulated WD agreed well with the observed values (Table II). WD were generally underestimated during the 2011–2012 growing season for all drainage systems except for $D_{0.9}L_{30}$, in which WD were overestimated

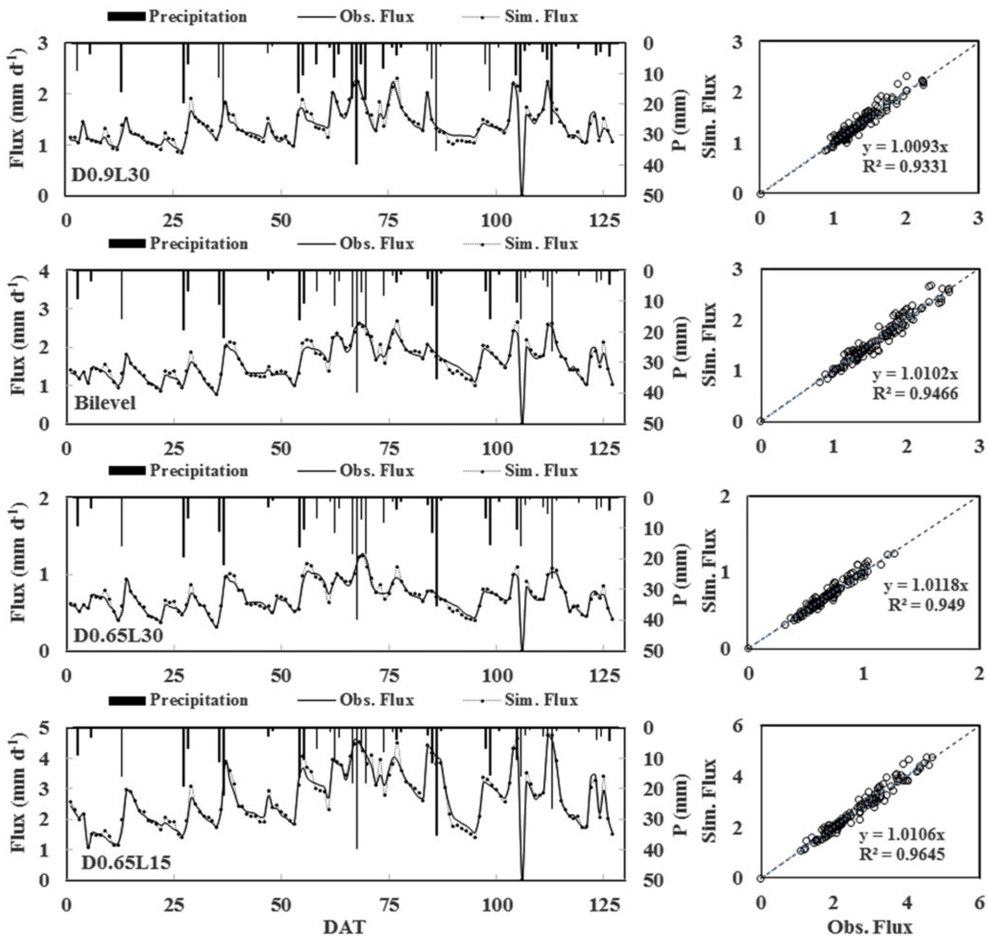

Figure 3. Temporal variations of drain discharges and precipitation (P) during the 2011–2012 growing season (the calibration period) for the four drainage systems. [Colour figure can be viewed at wileyonlinelibrary.com]

by less than 1%. In general, higher accuracy in estimating DF and WD was obtained for the $D_{0.65}L_{15}$ while the highest error was observed for the $D_{0.65}L_{30}$ during the calibration period (Table II).

The calibrated model was then applied to simulate DF and WD for different drainage systems during the 2015–2016 growing season (the validation period). The agreement between observed and simulated DF and WD was quantitatively assessed using the RMSE and MBE statistics (Table II). The model performance criteria for the validation period indicated the strong predictive capability of the model. EF, RMSE and MBE for DF ranged from 0.84–0.86, 0.4–1.02 and 0.06–0.17 mm day^{-1}, respectively, across different drainage systems, while for WD, the considered indices ranged from 0.89–0.96, 1.67–4.54 and – (0.16–0.63) cm, respectively. Table II indicates that overestimation was about 6.4–7.9% for DF and 2.8–3.8% for WD.

The comparison between simulated and measured values of DF with the 1: 1 line in Figure 5 also indicated that HYDRUS (2D/3D) can be successfully used to predict daily fluctuations of DF for different drainage systems in the 2015–2016 growing season. The average observed DF for the Bilevel, $D_{0.65}L_{15}$, $D_{0.65}L_{30}$ and $D_{0.9}L_{30}$ drainage systems during the validation period were 1.78, 2.18, 0.87 and 1.1 mm day^{-1}, respectively, while the corresponding simulated values were 1.91, 2.35, 0.94 and 1.1 mm day^{-1}, respectively. In addition, the determination coefficients varied in the range 0.91–0.93 across different drainage systems, indicating the strong predictive capability of the model.

Figure 6 compares temporal variations of simulated and observed WD for various drainage systems during the cropping cycles of 2015–2016 (the validation data set). Generally, simulated WD agreed well with observed values, with the determination coefficients ranging from 0.83 to 0.97. The close match between simulated and observed daily values of WD, as well as their seasonal trends, can be found in Figure 6. Better results were obtained for seasonal WD averages than for daily values: seasonal averages of observed WD for the $D_{0.9}L_{30}$, Bilevel, $D_{0.65}L_{30}$ and $D_{0.65}L_{15}$ drainage systems during

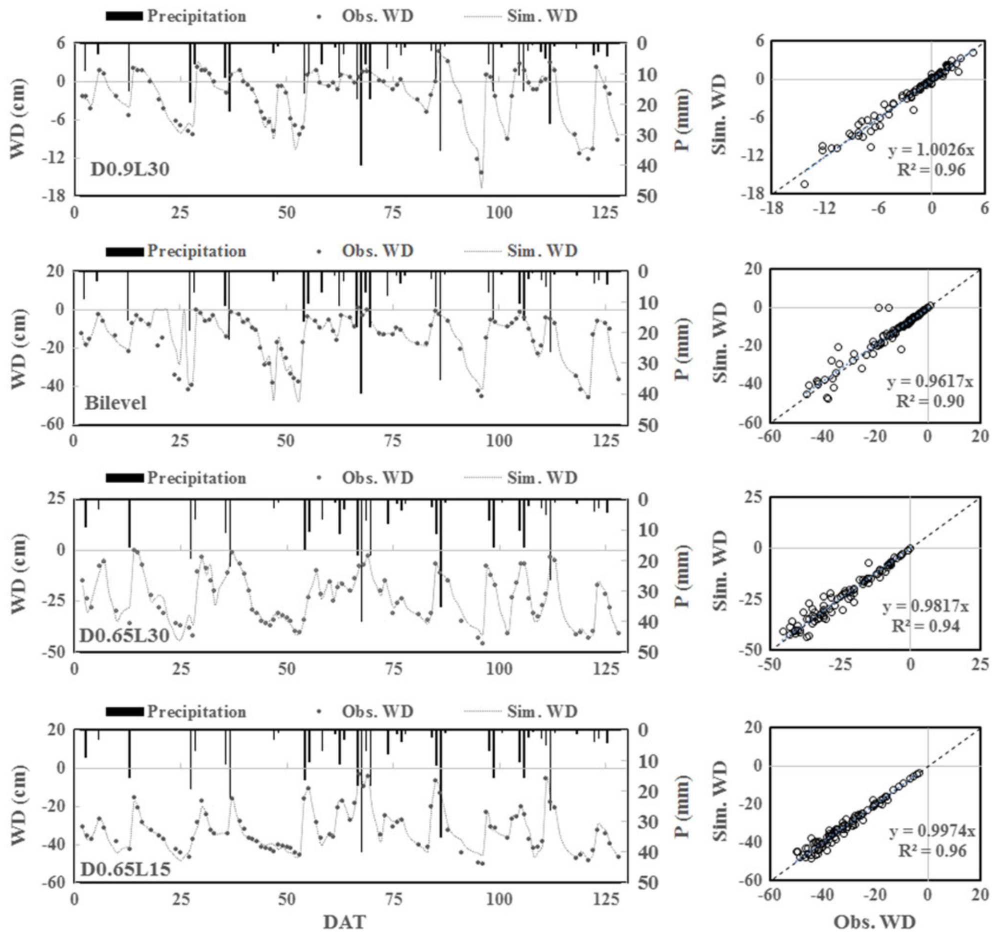

Figure 4. Temporal variations of the groundwater table depth (WD) and precipitation (P) during the 2011–2012 growing season (the calibration period) for the four drainage systems. [Colour figure can be viewed at wileyonlinelibrary.com]

Table II. The criteria indices comparing the observed and simulated drain discharges (DF) and groundwater table depths (WD) during the calibration (the 2011–2012 growing season) and validation periods (the 2015–2016 growing season)

Year	Parameter	Criteria index	Drainage systems			
			$D_{0.9}L_{30}$	Bilevel	$D_{0.65}L_{30}$	$D_{0.65}L_{15}$
2011–2012	DF	MBE (mm day^{-1})	−0.01	−0.01	−0.01	−0.02
		RMSE (mm day^{-1})	0.09	0.11	0.05	0.18
		EF	0.92	0.94	0.94	0.96
	WD	MBE (cm)	−0.01	0.10	0.13	0.25
		RMSE (cm)	0.37	1.30	1.75	2.23
		EF	0.99	0.99	0.98	0.96
2015–2016	DF	MBE (mm day^{-1})	−0.07	−0.13	−0.06	−0.17
		RMSE (mm day^{-1})	0.46	0.85	0.40	1.02
		EF	0.84	0.84	0.86	0.85
	WD	MBE (cm)	−0.16	−0.45	−0.53	−0.63
		RMSE (cm)	1.67	3.96	3.89	4.54
		EF	0.91	0.92	0.96	0.89

the validation period were −16.4, −44.8, −42.2 and −47.3 cm, respectively, while corresponding simulated values were −15.1, −44.9, −43.2 and −48.3 cm, respectively. A visual inspection of scatter plots in Figure 6, which compares observed and HYDRUS-estimated WD, clearly indicates the high potential of the

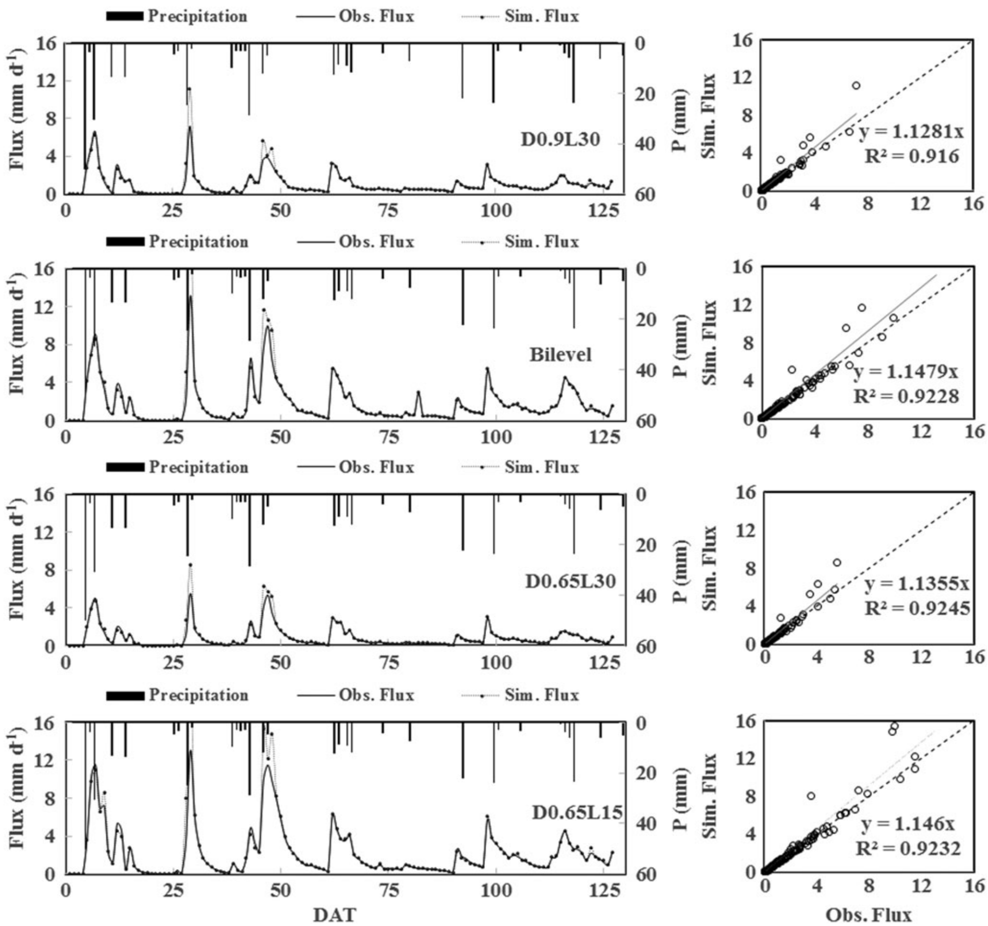

Figure 5. Temporal variations of drain discharges and precipitation (*P*) during the 2015–2016 growing season (the validation period) for the four drainage systems.

HYDRUS (2D/3D) modelling. Note the high values of the determination coefficients for various drainage systems (0.83–0.97) (Figure 6).

The results for the simulated WD and DF during the calibration (cropping cycles of 2011–2012) and validation (cropping cycles of 2015–2016) periods clearly represent a slight variance in the model's performance between various drainage systems. Such results may be attributed to different volumes of water flowing through the preferential flow paths formed during the drainage periods in various drainage systems. Such paths form when paddy soils crack when being drained (Tournebize *et al*., 2006; Janssen and Lennartz, 2009). The cracks may originate in the backfilled trench and expand further with time. While the number of cracks depend on the drainage design parameters (Darzi-Naftchali *et al*., 2017), they affect the volume of preferential flow in different drainage systems. Hence, the model may perform slightly less well in capturing water flow in paddy soils when the dual-porosity model is not considered (Garg *et al*., 2009; Sander and Gerke, 2009). Moreover, the model performance may be affected by neglecting the temporal variations of soil hydraulic parameters during the simulation periods. In fact, while the appearance and disappearance of cracks with different susceptibilities to swelling and shrinkage may cause dynamic changes in hydraulic conditions in paddy soils as a result of wetting and drying cycles (Sander and Gerke, 2007; Garg *et al*., 2009), we considered hydraulic properties to be constant over the whole growing season.

Overall, both the visual inspection of the scatter plots and the calculated values of the criteria indices, which compare the observed and HYDRUS (2D/3D)-estimated DF and WD during both growing seasons (the calibration period of 2011–2012 and the validation period of 2015–2016), clearly indicate the high potential of the HYDRUS (2D/3D) modelling. There was a close match between the observed and simulated data, with acceptable errors in all drainage systems. This capability makes the model applicable for the assessment of different groundwater table management strategies during the canola growing season. Moreover, simulated groundwater table profiles clearly indicate that HYDRUS (2D/3D) is a suitable tool for predicting

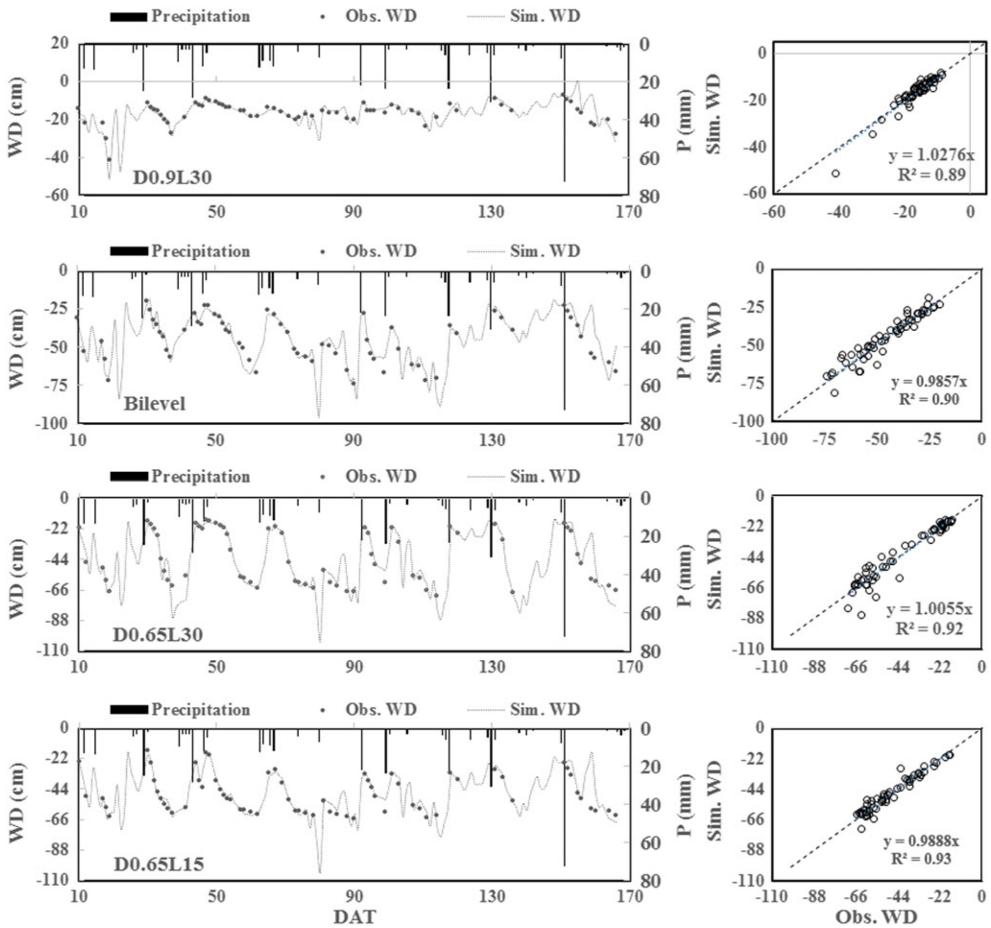

Figure 6. Temporal variations of the groundwater table depth (WD) and precipitation (P) during the 2015–2016 growing season (the validation period) for the four drainage systems. [Colour figure can be viewed at wileyonlinelibrary.com]

groundwater table fluctuations after irrigation or rainfall even in the presence of crops. The high accuracy of HYDRUS (2D/3D) is mainly due to the use of a deterministic approach for simulating soil water dynamics based on the Richards equation (Doltra and Munoz, 2010). Earlier research has also demonstrated the high potential of HYDRUS (2D/3D) for simulating soil water dynamics in different drained fields (Janssen and Lennartz, 2009; Garg *et al*., 2009; Tan *et al*., 2014; Li *et al*., 2014, 2015). For example, Tan *et al*. (2014) demonstrated that the soil water regime in lowland paddy fields under different water managements can be successfully modelled with HYDRUS-1D, obtaining RMSE for pressure heads 1.80–9.43 cm, with a mean of 5.17 cm, and EF 0.56–0.94, with a mean of 0.80. Their reported RMSE and EF were largely lower than those of Wang *et al*. (2010). Based on a 2-year field investigation, the HYDRUS-1D software package was used to simulate water movement in experimental paddy fields under various water irrigation and drainage managements. Their results showed only minor differences between measured and simulated water contents (RMSE = 10–20 mm and EF = 0.79–0.91) during the entire cropping cycles (Tan *et al*., 2015). Li *et al*. (2014, 2015) reported a very good correspondence between observed and simulated pressure heads (with EF = 0.97 and RMSE = 2.61 cm for the calibration period and EF = 0.94–0.95 and RMSE = 2.86–9.54 cm for the validation period), when simulating water movement and water losses in a direct-seeded rice field using HYDRUS-1D. Phogat *et al*. (2010) studied a micro-lysimeter system to test the capability of HYDRUS-ID to model the water balance and salt build-up in the soil under a rice crop irrigated with waters of different salinities. The low values of RMSE (10–20 mm) reported in their research indicate a good agreement between measured and modelled bottom flux values. Moreover, differences in means between measured and predicted values of bottom fluxes, as tested by a paired t-test, were also not found significant at P = 0.05, which verified the applicability of the HYDRUS-1D to simulate percolation from micro-lysimeters under a rice crop.

CONCLUSION

Using a 2-year field investigation, we evaluated the accuracy of the HYDRUS (2D/3D) model to simulate soil water dynamics under different drainage systems during rainfed canola cropping in paddy fields. HYDRUS (2D/3D) was able to capture the temporal fluctuations of groundwater table depths (RMSE = 0.05–1.02 and EF = 0.84–0.96) caused by variations in precipitation, evaporation, crop water demand and percolation during both cropping cycles. Both the seasonal trend and mean values of water fluxes simulated by HYDRUS-2D were in good agreement with corresponding observed values (RMSE = 0.01–0.63 and EF = 0.89–0.99), indicating that the model is well suited for experimental field conditions. Small differences were found in the model's performance for various drainage systems, which may have been caused by neglecting preferential flow and using the single-porosity flow model. Such differences may be expected when assuming constant soil hydraulic parameters thorough the simulation process while dynamic changes in hydraulic properties may have occurred as a result of wetting and drying cycles. While such considerations may improve simulation results, both visual inspection of the scatter plots and calculated values of criteria indices clearly indicate the high potential of HYDRUS (2D/3D) modelling in our research. Hence, it can be concluded that the HYDRUS (2D/3D) model, rather than labour- and time-consuming and expensive field investigations, can be reliably used for determining the optimal drainage system for the northern paddy fields of Iran.

ACKNOWLEDGEMENTS

The authors wish to thank the Sari Agricultural Sciences and Natural Resources University for providing the study area for field investigation. Also, the authors would like to thank the University of Zabol for financing the project.

REFERENCES

Ajdari K, Singh DK, Singh AK, Khanna M. 2007. Modeling of nitrogen leaching from experimental onion field under drip fertigation. *Agricultural Water Management* **89**: 15–28.

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper 56, Rome, Italy. 300 pp.

Cameira MR, Fernando RM, Pereira LS. 2003. Monitoring water and NO3-N in irrigated maize fields in the Sorraia Watershed, Portugal. *Agricultural Water Management* **60**: 199–216. https://doi.org/10.1016/S0378-3774(02)00175-0.

Cote CM, Bristow KL, Charlesworth PB, Cook FJ, Thorburn PJ. 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irrigation Science* **22**: 143–156.

Crevoisier D, Popova Z, Mailhol JC, Ruelle P. 2008. Assessment and simulation of water and nitrogen transfer under furrow irrigation. *Agricultural Water Management* **95**: 354–366.

Darzi-Naftchali A, Mirlatifi SM, Shahnazari A, Ejlali F, Mahdian MH. 2013. Effect of subsurface drainage on water balance and water table in poorly drained paddy fields. *Agricultural Water Management* **130**: 61–68.

Darzi-Naftchali A, Shahnazari A, Karandish F. 2017. Nitrogen loss and its health risk in paddy fields under different drainage managements. *Paddy and Water Environment* **5**(1): 157–145.

Doltra J, Munoz P. 2010. Simulation of nitrogen leaching from a fertigation crop rotation in a Mediterranean climate using the EU-Rotate-N and HYDRUS (2D/3D) models. *Agriculture Water Management* **97**: 277–285.

Feddes RA, Kowalik PJ, Zaradny H. 1978. Simulation of field water use and crop yield. In *Simulation Monographs*. Pudoc: Wageningen.

Fernández JE, Sławiński C, Moreno F, Walczak RT, Vanclooster M. 2002. Simulating the fate of water in a soil-crop system of a semi-arid Mediterranean area with the WAVE 2.1 and the EURO-ACCESS-II models. *Agricultural Water Management* **56**: 113–129.

Garg KK, Das BS, Safeeq M, Bhadoria PBS. 2009. Measurement and modeling of soil water regime in a lowland paddy field showing preferential transport. *Agricultural Water Management* **96**(12): 1705–1714.

Jafari-Talukolaee M, Ritzema H, Darzi-Naftchali A, Shahnazari A. 2016. Subsurface drainage to enable the cultivation of winter crops in consolidated paddy fields in northern Iran. *Sustainability* **8**(249): 1–19.

Janssen M, Lennartz B. 2009. Water losses through paddy bunds: methods, experimental data, and simulation studies. *Journal of Hydrology* **369**(1–2): 142–153.

Karandish F, Šimůnek J. 2016a. A field-modeling study for assessing temporal variations of soil–water–crop interactions under water-saving irrigation strategies. *Agricultural Water Management* **178**: 291–303.

Karandish F, Šimůnek J. 2016b. Numerical and machine-learning modeling of soil water content for sustainable water management in agriculture under water stress. *Journal of Hydrology* **543**: 892–909.

Lazarovitch N, Poulton M, Furman A, Warrick AW. 2009. Water distribution under trickle irrigation predicted using artificial neural networks. *Journal of Engineering Mathematics* **64**(2): 207–218.

Li Y, Šimůnek J, Jing L, Zhang Z, Ni L. 2014. Evaluation of water movement and water losses in a direct-seeded-rice field experiment using Hydrus-1D. *Agricultural Water Management* **142**: 38–46.

Li Y, Šimůnek J, Zhang Z, Jing L, Ni L. 2015. Evaluation of nitrogen balance in a direct-seeded-rice field experiment using Hydrus-1D. *Agricultural Water Management* **148**: 213–222.

Mubarak I. 2009. Effect of temporal variability in soil hydraulic properties on simulated water transfer under high-frequency drip irrigation. *Agricultural Water Management* **96**(11): 1547–1559.

Neitsch SL, Arnold JG, Kiniry JR, Williams J. 2005. *Soil and Water Assessment Tool (SWAT), theoretical documentation*. Blackland Research Center, Grassland, Soil and Water Research Laboratory, Agricultural Research Service: Temple, Tex.

Nishat S, Guo Y, Baetz BW. 2007. Development of a simplified continuous simulation model for investigating long-term soil moisture fluctuations. *Agricultural Water Management* **92**: 53–63.

Ogino Y, Ota S. 2007. The evolution of Japan's rice field drainage and development of technology. *Irrigation and Drainage* **56**: 69–80.

Panigrahi B, Panda SN. 2003. Field test of a soil water balance simulation model. *Agricultural Water Management* **58**: 223–240.

Parchami-Araghi F, Mirlatifi SM, Ghorbai-Dashtaki S, Mahdian MM. 2013. Point estimation of soil water infiltration process using artificial neural networks for some calcareous soils. *Journal of Hydrology* **481**(25): 35–47.

Phogat V, Yadav AK, Malik RS, Kumar S, Cox J. 2010. Simulation of salt and water movement and estimation of water productivity of rice crop irrigated with saline water. *Paddy and Water Environment* **8**(4): 333–346.

Rahil MH. 2007. Simulating soil water flow and nitrogen dynamics in a sunflower field irrigated with reclaimed wastewater. *Agricultural Water Management* **92**(3): 142–150.

Ramos TB, Šimůnek J, Gonçalves MC, Martins JC, Prazeres A, Pereira LS. 2012. Two-dimensional modeling of water and nitrogen fate from sweet sorghum irrigated with fresh and blended saline waters. *Agricultural Water Management* **111**: 87–104.

Sander T, Gerke HH. 2007. Preferential flow patterns in paddy fields using a dyetracer. *Vadose Zone Journal* **6**(1): 105–115.

Sander T, Gerke H. 2009. Modelling field data of preferential flow in paddy soil induced by earthworm burrows. *Journal of Contaminated Hydrology* **104**(1–4): 126–136.

Šimůnek J, van Genuchten MT, Šejna M. 2008. Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal* **7**(2): 587–600. https://doi.org/10.2136/VZJ2007.0077.

Šimůnek J, van Genuchten MT, Šejna M. 2016. Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone Journal* **15**(7): 1–25.

Siyal AA, Skaggs TH. 2009. Measured and simulated soil wetting patterns under porous clay pipe sub-surface irrigation. *Agricultural Water Management* **96**(6): 893–904.

Skaggs TH, Trout TJ, Šimůnek J, Shouse PJ. 2004. Comparison of HYDRUS (2D/3D) simulations of drip irrigation with experimental observations. *Journal of Irrigation and Drainage Engineering* **130**: 304–310.

Tafteh A, Sepaskhah AR. 2012. Application of HYDRUS-1D model for simulating water and nitrate leaching from continuous and alternate furrow irrigated rapeseed and maize fields. *Agricultural Water Management* **113**: 19–29.

Tan X, Shao D, Liu H. 2014. Simulating soil water regime in lowland paddy fields under different water managements using HYDRUS-1D. *Agricultural Water Management* **132**: 69–78.

Tan X, Shao D, Gu W, Liu H. 2015. Field analysis of water and nitrogen fate in lowland paddy fields under different water managements using HYDRUS-1D. *Agricultural Water Management* **150**: 67–80.

Tournebize J, Watanabe H, Takagi K, Nishimura T. 2006. The development of a coupled model (PCPF-SWMS) to simulate water flow and pollutant transport in Japanese paddy fields. *Paddy and Water Environment* **4**(1): 39–51.

Vanclooster M, Viaene P, Christiaens K, Ducheyne S. 1996. WAVE, *Release 2.1: Instruction Manual*. Institute for Land and Water Management, Katholieke Universiteit Leuven:Vital Decosterstraat 102, B-3000 Leuve, Belgium.

Van Dam JC, Huygen J, Wesseling JG, Feddes RA, Kabat P, van Walsum PEV, Groenendijk P, van Diepen CA. 1997. *Theory of SWAP Version 2.0: Simulation of Water Flow, Solute Transport and Plant Growth in the Soil–Water–Atmosphere–Plant Environment*. DLO Win and Staring Centre, Wageningen, Report/Wageningen Agricultural University, Department Water Resources No. 71.

van Genuchten MT. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *American Journal of Soil Science Society* **44**: 892–898.

Wagenet RJ, Hutson JL. 1989. *LEACHM: Leaching Estimation and Chemistry Model: a Process Based Model of Water and Solute Movement Transformations, Plant Uptake and Chemical Reactions in the Unsaturated Zone*. Continuum vol. 2, Version 2, Water Resources Institute, Cornell University: Ithaca, New York.

Wang H, Ju X, Wei Y, Li B, Zhao L, Hu K. 2010. Simulation of bromide and nitrate leaching under heavy rainfall and high-intensity irrigation rates in North China Plain. *Agricultural Water Management* **97**(10): 1646–1654.

Wessolek G. 1989. *Einsatz von Wasserhaushalts-Und Photosynthese-modellen in der Ökosystemanalyse*. Landschaftsentwicklung und Umweltforschung, Schriftenreihe des FB 14, TU Berlin 61: Berlin, Germany; 164 (in German).